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Office of Naval Research
Department of the Navy
800 North Quincy Street
Arlington, VA 22217-5000

ATTN: Jim Smith, Code 1211

SUBJ: Final Report, Contract N00014-89-J-1967

Dear Jim:

The attached represents the Final Report under the above referenced contract, covering the time period from 1 May 1989 to 31 December 1990. Under this contract, two applications of higher order spectral processing were investigated: detection with full and half beam sensor systems, and remote sensing of sound fields using laser Doppler velocimetry techniques. The technical details of this work were documented in two technical reports (Barlett, 1990 and Wilson and Hardwicke, 1991) and a technical paper (Barlett and Hsu, 1991). The purpose of this Final Report is to summarize briefly the results described more fully in these other documents.

If you have any questions or require further information, please call.

Sincerely,
Gary R. Wilson
Gary R. Wilson
Signal Physics Group

1. DETECTION WITH FULL AND HALF BEAM SENSOR SYSTEMS

The results of the application of higher order spectral processing to detection of acoustic signals from full and half beam sensor systems is documented in Wilson and Hardwicke (1991), and are summarized in this section. In this report we discussed the detection performance of a variety of higher order spectra for a variety of signals. Of particular significance is the introduction of a new type of higher order spectra called *non-stationary* higher order spectra. Non-stationary higher order spectra are not the stationary higher order spectral representations of non-stationary processes, but are in fact different spectra which contain the stationary higher order spectra as a subset of their domain. It was shown quantitatively through theoretical predictions and simulations in the above referenced report that these type of spectra can perform better at detecting non-stationary signals under certain conditions than the traditional stationary spectra. For the first time, small sample statistics were derived and applied to the detection performance rather than asymptotic statistics, resulting in a more accurate performance prediction for typical sample sizes.

The use of cross power spectrum and auto power spectrum to detect narrowband signals was examined first. Even though the cross and auto power spectra are not higher order spectra, the issue addressed in this report was whether or not cross-channel processing can result in an increase in detection performance commensurate with higher order spectral processing. In an incoherent noise field, the cross power spectrum of the noise asymptotically approaches zero, so it should achieve some processing gain over auto power spectrum processing for narrowband signals. However, it was shown theoretically that if the cross power spectrum is applied to the half beams of a towed array and the auto power spectrum is applied to the full beam of a towed array, then in an isotropic noise field the cross power spectrum actually performs about 1 dB worse than the auto power spectrum. This result is due to the fact that the noise levels in the half beams are approximately 3 dB more than the noise level in the full beam due to the decreased directionality of the half beams. Thus based on this theoretical analysis we would not expect cross power spectrum processing to result in improved detection performance over the auto power spectrum under the conditions analyzed.

Having determined that cross-channel processing is not expected to result in any detection gains for half beam processing compared to full beam processing in an isotropic noise field, we then restricted our attention to single channel processing and examined the detection performance of the auto power spectrum compared to various auto higher order spectra. We considered the case of narrowband detection when two harmonically related narrowband components a‌ı ; present. Higher order spectra are designed to detect distinct frequency components that are coherently related. Two narrowband harmonics can be considered a case of a cyclo-stationary process, so we first examined the detection performance of the *non-stationary* power spectrum, which is related by a simple transform to the spectral correlation. We derived in this report (Wilson and Hardwicke, 1991) the small sample density function for the magnitude of the spectral correlation and used it to predict the spectral correlation's detection performance. We showed that the spectral correlation can theoretically perform significantly better than the power spectrum under conditions analyzed in the above referenced report, but that it is necessary to use the unnormalized spectral correlation rather than the normalized spectral correlation to achieve this improvement. We also examined the detection performance of the bispectrum and showed that it also theoretically performs better than the power spectrum when the unnormalized bispectrum is used.

We also considered the case of finite duration (transient) signals and compared the detection performance of the spectral correlation (non-stationary power spectrum) and stationary power spectrum. We derived the small sample density function for the spectral correlation when the transient signal is considered to be a single deterministic (but unknown) waveform. In this case the spectral correlation also performs better than the power spectrum under conditions analyzed in the above referenced report.

2. REMOTE SENSING OF SOUND FIELDS USING LASER DOPPLER VELOCIMETRY

The results of applying higher order spectral processing techniques to the problem of remote sensing of sound fields using laser Doppler velocimetry are documented in Barlett (1990) and Barlett and Hsu (1991), and are summarized in this section. In our investigation of higher order processing methods for remote acoustic sensing we sought to understand the principles of laser Doppler velocimetry (LDV) based remote acoustic detection, the general characteristics of signals produced by LDV sensors, factors which limit the sensitivity of such systems, and the relative merits of several different processing schemes for LDV acoustic sensors. The basic single particle forms of LDV signals for two optical arrangements, the differential and reference beam geometries, were derived and used as the basis for constructing an LDV signal simulation program for use in signal processing studies. The simulated signals consisted of a "photon stream" which represented the output from a photon-counting detector. The noise contribution due to the discrete nature of the detection process (shot noise) was simulated using a Poisson distributed random number generator. Additional terms were incorporated in the signal which allowed the user to specify the relative contributions of random phase noise and additive Gaussian noise to the signal.

In constructing a simulation model for an LDV signal we attempted to include the signal properties which are most relevant from a signal processing perspective. Comparisons of results obtained from several different signal processing algorithms using both simulated LDV signals and a sample of actual LDV data suggested that the simulated signals were a reasonable representation of signals which may be obtained from an actual LDV acoustic sensor. The signal simulation program was used extensively in the signal processing studies which followed and provided a great deal of flexibility in specifying the signal characteristics (Doppler signal strength, signal to noise ratios, detected photon flux, etc.) for determinations of the merits and limitations of various signal processing schemes.

The initial signal processing study utilized power spectral processing to identify the effects of the model noise sources on the detectability of the Doppler signal. The relationship between the Doppler signal strength and the underlying acoustic field was established and general relationships were determined which related the maximum tolerable noise levels from the various sources to the minimum Doppler signal which could be visually identified in a power spectral plot. Several limitations on Doppler signal detectability were empirically determined during the course of the study. Lower limits were established for the detected photon flux as a function of Doppler signal strength for a "noiseless" LDV acoustic sensor. The effects of the various model noise sources were then investigated and maximum noise levels as a function of Doppler signal strength were determined. Based on the empirical results of this study, one can conclude that an extension of presently demonstrated detection sensitivity by one or two orders of magnitude will require a very "quiet" LDV system if one employs power spectral processing techniques.

Motivated by the relationship between signal detectability and detected photon flux, a set of calculations was then performed to determine the viability of detecting weak acoustic fields in a laboratory demonstration using LDV techniques. The scattered photon flux at a photodetector was determined for two possible LDV configurations constrained to operate in a backscatter geometry. The sensitivity to the various optical parameters of the LDV system was also determined . Uncertainties about both the value and applicability of the seawater scattering coefficient used in the calculations raised concerns about the validity of the results. However, based on the inputs used in the calculations, a laboratory demonstration of LDV acoustic sensing appears feasible at sound levels which are one or two orders of magnitude less than those presently detected in laboratory measurements.

An initial study of several potential higher order processing techniques was conducted which may provide better discrimination against certain noise sources than can be obtained from power spectral techniques. The methods used in this study employed spectral correlation techniques which make use of the fixed phase relationships between various spectral components. An empirical evaluation of a normalized spectral correlation function known as the co-intensity was performed and compared with results from power spectral analyses. The comparisons indicated enhanced processing gain in the presence of Gaussian noise sources using co-intensity processing, and suggested detection of the Doppler signal may be possible in Gaussian noise backgrounds with levels which are approximately twice as large as the maximum tolerable noise levels found in the power spectral processing studies. A more detailed determination of the limitations of this technique remains for a future study.

A new algorithm, which utilizes spectral correlation techniques and attempts to exploit symmetries which exist in the LDV spectrum, was developed. Comparisons of results from this "folded co-intensity" with conventional co-intensity results suggested that the folded co-intensity technique may provide enhanced detection coherence for this form of signal.

An experimental program was also initiated to supplement the signal processing studies of LDV acoustic sensors. The primary focus of the experimental measurements was the characterization of noise associated with laser measurement systems such as LDV sensors for frequencies below 10 kHz. In the signal processing studies it was determined that intensity fluctuations of the illuminating beams of an LDV sensor limit the attainable sensitivity for detection of an acoustic field using power spectral processing. However initial indications based on processing of simulated and experimental LDV data, as reported in Barlett (1990), suggested that higher order techniques may extend the sensitivity of an LDV sensor provided the noise background is incoherent. The experimental measurements addressed three issues relating to the expected noise characteristics for an LDV sensor: (1) the spectral content of noise from simple laser/detector systems at low frequencies, (2) the coherence of noise in such systems, and (3) the effects of an acoustic source on the level and structure of noise.

The experimental noise levels measured in the laser/detector system were found to have a nearly flat spectrum over the bandwidths we investigated. Low frequency noise ($\leq$ 10 Hz) was observed which seemed to be associated with couplings of the laser and detector to largescale vibration sources such as building structural vibrations. Pneumatic isolation of the optical table reduced the contribution of these sources to the observed noise spectra.

The coherence of noise below 10 kHz was investigated using a normalized spectral correlation (co-intensity) function. Comparisons were made between co-intensity distributions from noise data and distributions from computer generated quantized Gaussian inputs using both statistical measures of the distributions and the Kolmogorov-Smirnov two-sample (KS-2) test. The results suggested that except at the widest bandwidths studied, the noise appears to be incoherent. The use of higher order processing methods to provide some level of discrimination against noise thus appears tractable.

Finally, the effects of an acoustic source on the observed noise levels in a laser measurement system (such as an LDV acoustic sensor) was investigated using two optical configurations with different pathlengths. A narrowband peak at the acoustic source frequency was observed for the system with the longer pathlength; the presence of a nearby acoustic source produced no significant effect of the noise level of the shorter pathlength arrangement. The results imply that measurements can be made in the presence of an acoustic source provided care is taken to control the optical pathlengths in the system and to minimize potential couplings of the acoustic field to the optics and laser.

REFERENCES

Barlett, Martin L. (1990). "Signal Processing Studies of a Simulated Laser Doppler Velocimetry-Based Acoustic Sensor," Applied Research Laboratories Technical Report No. 90-33 (ARL-TR-90-33), Applied Research Laboratories, The University of Texas at Austin.

Barlett, Martin L. and Hsu, J. W. (1991). "Low Frequency Spectral Content and Coherence of Noise in Laser Measurement Systems," Applied Research Laboratories Technical Paper No. 91-3 (ARL-TP-91-3), Applied Research Laboratories, The University of Texas at Austin. To be submitted to the Journal of Applied Optics.

Wilson, Gary R. and Hardwicke, Keith R. (1991). "Non-Stationary Higher Order Spectral Analysis," Applied Research Laboratories Technical Report No. 91-8 (ARL-TR-91-8), Applied Research Laboratories, The University of Texas at Austin.